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IS TIME-DOMAIN SPECTRUM MATCHING PROCEDURE ACCURATE AND EFFICIENT FOR RESPONSE HISTORY ANALYSIS OF BUILDINGS?

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ABSTRACT

Nonlinear response history analysis (RHA) is now being increasingly used to estimate engineering demand parameters (EDPs)—floor displacements, story drifts, member forces, member deformations, etc.—of buildings and special structures subjected to ground motions. As an input, RHA requires a small set of earthquake records. These records should be properly selected and scaled in compliance with site-specific hazard conditions to ensure that they provide accurate and efficient estimates of "expected" median demands. Most of the existing procedures for modifying ground motion records fall into one of two categories: amplitude-scaling and spectrum matching (SM). While amplitude-scaling techniques change intensity of the ground motion record, SM methods alter the record waveform to tightly match its response spectrum to a target (or design) spectrum. Considering the limited research on SM methods for three-dimensional (3D) nonlinear RHA of buildings and the lack of consensus in published studies, this investigation comprehensively examines a time-domain SM method for nonlinear RHAs of single- and multi-story buildings having symmetric and asymmetric plans subjected to two components of ground motions, simultaneously. For this evaluation, 48 single-story and nine multi-story buildings were modelled. The structural systems were subjected to sets of seven records modified according to the SM procedure and ASCE/SEI 7-10 ground motion scaling method, and their responses were compared against the benchmark values in order to test the accuracy and efficiency of both procedures. The benchmark corresponds to the median value of an EDP obtained from RHAs of the structural systems due to the ensemble of 30 "unscaled" records. This evaluation shows that: (1) The SM method provides accurate estimates of median EDP values and reduced record-to-record variability of the responses; (2) The SM method is found to be more accurate compared to the ASCE/SEI 7-10 scaling procedure for 3D analysis of asymmetric-plan buildings; however, it reduces the variability of EDPs associated with aleatoric uncertainty in ground motion records.

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INTRODUCTION

Performance-based procedures for evaluating existing buildings and proposed designs of new buildings in the U.S. require response history analyses (RHAs) for an ensemble of earthquake records in order to determine engineering demand parameters (EDPs) for validation of targeted performance criteria. Ground motion records selected for RHAs often need to be scaled or modified to a seismic hazard level considered. Fraught with several challenging issues, selection and modification of ground motions necessary for nonlinear RHA remains a subject of much research in recent years.

Among many ground motion modification procedures, the most widely used are amplitude scaling and spectrum matching (Lilhanand and Tseng, 1988). In the first approach, only the amplitude of the record is modified, whereas spectral matching methods not only modify the record amplitude but also tailor its frequency content to match its response spectrum to a target spectrum. The objective of modifying records is to provide accurate and efficient estimates of structural responses. The term "accuracy" means that the modified records should provide median (or mean) responses close to the "exact" responses considering large population of records compatible with the hazard conditions specified. The term "efficiency" means that ground motions after modification should impose similar seismic demands to the structure. While large record-to-record variability in EDPs leads to uncertainties in design, and diminishes the confidence level, small record-to-record variability (dispersion) indicates that modified records represent well the target demand level. Thus, a reliable modification method should not only produce accurate but also efficient estimates of EDPs.

Earlier approaches to generate spectrum-compatible ground motions did not modify an actual record, but instead artificial ground motions were generated from white noise. This approach was found to be inaccurate and inefficient for structures responding in nonlinear range (Naeim and Lew, 1995; Hancock et al. 2006). Spectrum-compatible ground motions generated by adjusting the Fourier amplitude spectra were widely used in design of buildings, especially for base-isolated structures (Rizzo et al. 1975; Silva and Lee, 1987). Although this method has the advantage of using real ground motions, it was found that adjusting motions in frequency domain distorts their velocity- and displacement time series, and lead to ground motions with unrealistically high energy content (Naeim and Lew, 1995). An alternative solution in modifying ground motion records is adding wavelets in time domain. An early approach for time domain spectral matching was developed by Kaul (1978), and extended to multiple damping levels by Lilhanand and Tseng (1987, 1988). Based on the ideas of Lilhanand and Tseng (1987), Abrahamson (1992) developed the program "RspMatch". A modified version of this program called RspMatch2005 was developed by Hancock et al. (2006). Later, update versions of this program were developed by Grant (2013) and Al Atik and Abrahamson (2013); however, these computer codes are not easily available, and have not been extensively used in spectrum-matching related publications. For these reasons, we opt to use RspMatch2005 in this research. Few studies have been conducted to verify the accuracy of time-domain spectrum matching methods for structures responding in nonlinear range. Carballo (2000) and Bazurro and Luco (2006) found that the use of spectrum matched records could lead to underestimations of nonlinear seismic responses. Watson (2007) concluded that the discrepancies previously reported by Bazurro and Luco (2006) may be explained by errone2ous statistical assumptions. All these studies are limited to single degree of freedom systems (SDF) subjected to one component of ground motion. Lately, Grant and Diaferia (2013) investigated the effects of excessive manipulation by spectrum matching on structural response. It is shown that excessive manipulation of ground motions does not lead to significant bias in the results when compared with a rigorous point of comparison (POC) or benchmark.

Considering the contradictory conclusions in previous studies, this investigation comprehensively evaluates the adequacy of time-domain spectrum-matched seismic records for conducting nonlinear RHAs of single- and multi-story buildings with symmetric- and asymmetric-plan subjected to two horizontal components of ground motion (Reyes et al. 2014b). In addition, the spectrum matching (SM) method is compared against the ASCE/SEI 7-10 (henceforth abbreviated as ASCE7) scaling procedure.

GROUND MOTION ENSEMBLE

The 30 records selected for this investigation listed in Reyes et al. (2014a, 2014b) were recorded from seven shallow crustal earthquakes with moment magnitude 6.7 ± 0.2 , at closest fault distances ranging from 20 to 30 km, and with NEHRP site classification C (very dense soil or soft rock) or D (stiff soil). Shown in Figure 1 are the 5%-damped median response spectra of x and y components of the ground motions.

STRUCTURAL SYSTEMS

An extensive set of 48 single-story and nine multi-story symmetric and asymmetric-plan buildings were designed as detailed in (Reyes et al., 2014b). Three different plan shapes were utilized for both single-story and multi-story buildings; these are identified by letters R, L and T. Plan R ("Rectangular") stands for quasi-rectangular; plan T is symmetric about y-axis, and plan L is asymmetric about both x and y axes.

Single-Story Buildings

The group of buildings selected are 48 three-degree-of-freedom structures (32 of them having asymmetric-plan) with fundamental periods T_1 = 0.2, 0.5, 1, and 2 sec., and a response modification factor R_y equal to 2, 3, 5 and a value that leads to a linear elastic design. The lateral resisting system of the buildings consists of buckling-restrained braced frames with non-moment-resisting beam-column connections.

Figure 2 shows the plan shapes and bracing layouts of the buildings where the centers of mass and stiffness are marked. The earthquake design forces were determined by bi-directional linear response spectrum analysis of the building with the spectrum reduced by R_y. Further details of the structural systems including their natural periods, mode shapes, can be found in Reyes and Quintero (2014) and Quintero (2012). Table 1 shows the ratios of the uncoupled torsional to lateral frequencies (ω_θ / ω_x and ω_θ / ω_y) and ratios of eccentricities to radius of gyration (e_x/r and e_y/r). Note that structures with plans L and T have high eccentricities, and are torsionally-flexible, while structures with plan R has low eccentricities, and is torsionally-stiff. For structures with plans L and T, the ratios of uncoupled torsional to lateral frequencies are close to 1.0 indicating strong coupling between lateral and torsional motions (Kan and Chopra, 1976).

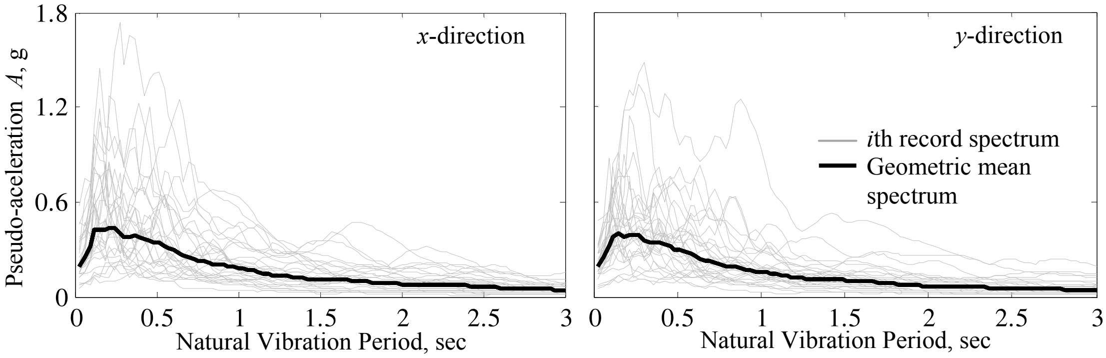


Figure 1. Geometric-mean pseudo-acceleration response spectra of 30 records for 5% damping; individual response spectra of the records are also shown.

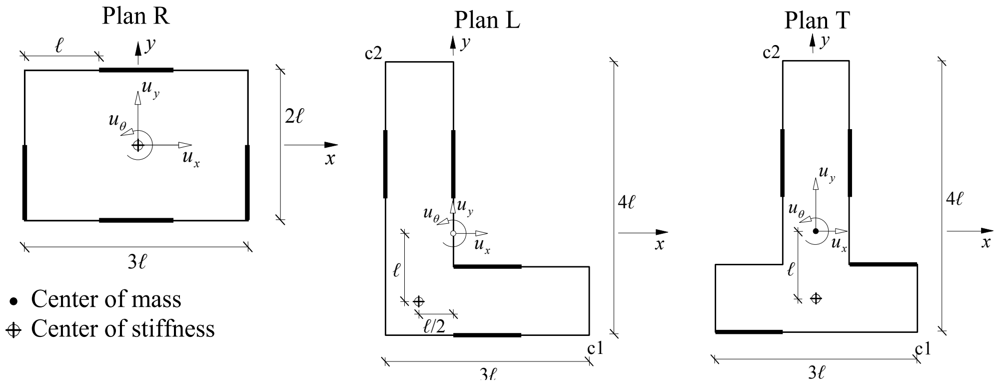


Figure 2. Schematic isometric and plan views of the selected structural systems with degrees of freedom, centers of mass and centers of stiffness; buckling-restrained braced frames are highlighted.

To verify that the selected buildings cover a broad range of torsional irregularities, the following irregularity factor was calculated for each building (ASCE7, 2010):

$$\beta = \Delta_{\max} / \Delta_{average} \tag{1}$$

where Δ_{max} is the maximum story drift and $\Delta_{average}$ is the average story drift at the two ends of the structure. The levels of torsional irregularity according to the ASCE7 are: (1) No torsional irregularity: $\beta < 1.2$; (2) Torsional irregularity: $1.2 \leq \beta \leq 1.4$ and (3) Extreme torsional irregularity: $\beta > 1.4$. The values of β are presented in Table 2 for R-, L- and T-plan buildings.

Table1. Ratio of the uncoupled torsional to lateral frequencies, static eccentricities, and normalized eccentricities.

Plan	$\frac{\omega_\theta}{\omega_x} = \frac{\omega_\theta}{\omega_y}$	$\frac{e_x}{r}$	$\frac{e_y}{r}$	$\frac{e_x}{3\ell^*}$	$\frac{e_y}{4\ell^*}$
R	1.73	0	0	0%	0%
L	0.92	0.42	0.85	16.7%	25%
T	0.94	0	0.77	0%	25%

* ℓ is defined in Figure 2

Table 2. Torsional irregularity factors.

Building	R	L	T
B	1.0	1.6	1.7

Multi-Story Buildings

The structures considered are nine asymmetric-plan hypothetical buildings with 5, 10 and 15 stories. These buildings were designed according to the 2009 International Building Code (see Eq. 1) (IBCO, 2009) to be located in Los Angeles, California, covering the levels of horizontal irregularity defined in the ASCE7 standard (ASCE, 2010)—torsional irregularity and extreme torsional irregularity. The lateral resisting system of the buildings consists of moment resisting frames. Their plan shapes are shown in Figure 3, where the moment resisting frames are highlighted. The buildings are identified by the letters R, L and T follow by the number of stories. The buildings have similar plan areas and floor weights with a span length of 30 ft (9.14 m) and a story height of 10 ft (3.05 m). The earthquake design forces were determined by bi-directional linear response spectrum analysis of the building with the design spectrum reduced by a response modification factor R_y=8. However, member sizes were governed by drift limits instead of strength requirements.

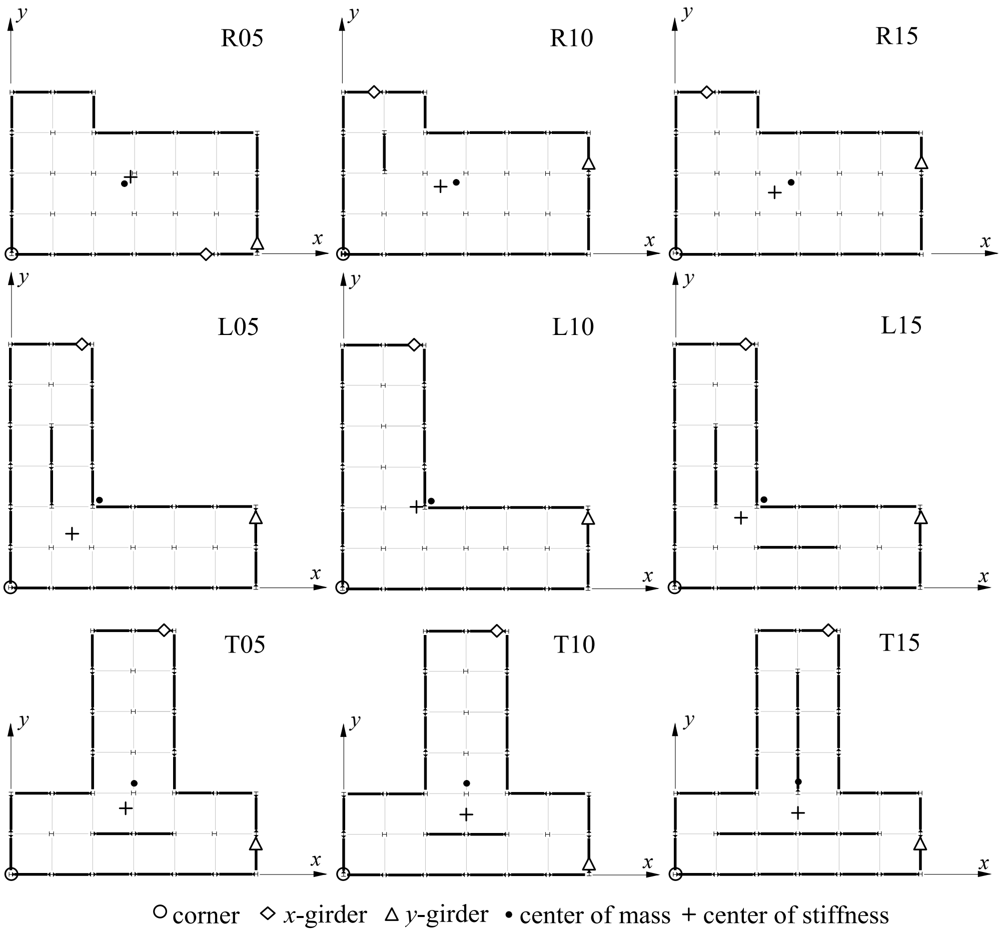


Figure 3. Plan views of the nine multi-story buildings selected.

The buildings were modeled using PERFORM-3D (CSI, 2009) computer program as follows: (1) Beams and columns were modeled by a linear element with tri-linear plastic hinges at the ends of the elements that can include in-cycle strength deterioration, but not cyclic stiffness degradation; the axial load-moment interaction for the columns was based on plasticity theory; (2) Panel zones were modeled as four rigid links hinged at the corners with a rotational spring that represents the strength and stiffness of the connection; (3) Ductility capacities of girders, columns, and panel zones were specified according to the ASCE/SEI 41-06 standard (ASCE/SEI, 2007); (4) Columns of moment resisting frames and the gravity columns were assumed to be clamped at the base; and (5) Effects of nonlinear geometry were approximated by a standard $P\text{-}\Delta$ formulation to account for secondary effects. The level of torsional irregularity was calculated for the nine buildings using Eq. 1. The buildings selected cover three levels of torsional irregularity as demonstrated in Table 3. Further details of their structural systems including fundamental periods, mode shapes, torsional irregularity factors etc. can be found in Reyes et al. (2014a, 2014b), Riaño (2013) and Arango (2013).

Table 3. Torsional irregularity factors.

Building	R05	R15	R10	L10	L15	T15	L05	T10	T05
B	1.00	1.10	1.13	1.20	1.26	1.30	1.35	1.41	1.43

COMPARATIVE EVALUATION OF SPECTRUM MATCHING AND ASCE7 SCALING PROCEDURE

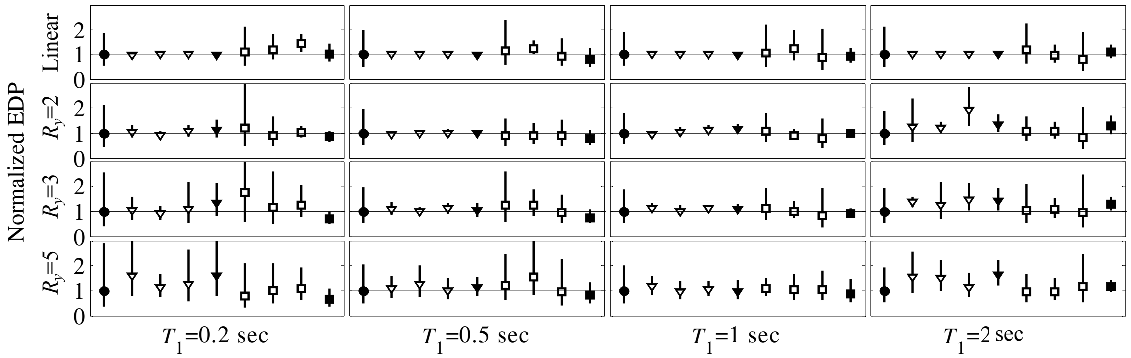
The structures were subjected to sets of seven records modified according to the SM and ASCE7 procedures and their responses were compared against the benchmark values, defined as the median EDP values due to the 30 "unscaled" seismic records. The step-by-step procedure used to implement the SM method is presented in Reyes et al. (2014b). Because the 30 ground motions selected were not intense enough to drive the multi-story buildings considered far into the inelastic range—an obvious requirement to test any scaling procedure—they were pre-amplified by a factor of 4.0. These pre-amplified ground motions are treated as "unscaled" records for this investigation (Reyes et al. 2014b). In order to be consistent in comparisons of the SM method with the ASCE7 procedure, geometric mean was used for the ASCE7 procedure even though this procedure requires mean. The use of "mean" instead of "geometric mean" would not affect the conclusions—provided that "mean" is consistently used for both scaling methods.

Single-Story Buildings

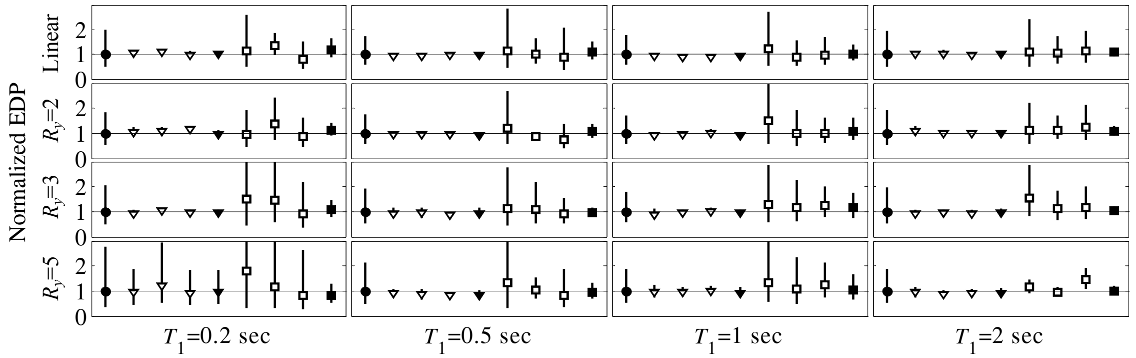
Figure 4 shows normalized displacement results of nonlinear RHAs for single-story buildings along x- and y-direction. Each part of this figure is a four-by-four array corresponding to sixteen combinations of R_y (increasing from top to bottom) and T_1 (increasing from left to right). The vertical axis of the plots is the displacement obtained from each set normalized by the corresponding benchmark value. The solid round marker and vertical line (first line in each panel) represent the normalized benchmark value ± one standard deviation (σ) assuming a lognormal distribution. A horizontal solid line crosses the round marker to make the comparison between sets and benchmark values easier. Figure 4 shows results obtained at three locations: The center of mass (C.M.), corner c1 and corner c2 (see Fig. 2). Normalized EDPs for each set are indicated with a marker and a vertical line representing the median $\pm\,\sigma$ assuming also a lognormal distribution. The marker assigned to each procedure is indicated in the legend at the bottom of the figures. Note that results correspond to the maximum absolute values of time histories of the EDPs.

The accuracy and efficiency of the SM and ASCE7 scaling procedures were examined by comparing the median EDPs due to various sets of seven modified ground motion pairs against the benchmark defined above. For each procedure, Figure 4 includes three sets of seven records randomly selected (called "SM-Rand" and "ASCE7-Rand") in order to evaluate the robustness of the selection phase, and one set of seven records selected by implementing an improved selection procedure (called "SM-Best" and "ASCE7-Best"). Suffix "-Best" means that the selection procedure was implemented using a common criterion to obtain a better estimation of EDPs, but the results are not necessarily better than those provided by randomly selected sets. The scaled records in set "ASCE7-Best" were selected by minimizing the discrepancy between the scaled spectrum of a record and the target spectrum over the period range from $0.2T_1$ to $1.5T_1$, and then identifying the final set of records as those with spectral acceleration values at T_1 close to the target spectrum. This selection procedure was proposed by Reyes and Kalkan (2011, 2012), and is not part of the ASCE7. The set "SM-Best" includes ground motions selected in steps 4 and 5 of the method presented in Reyes et al. (2014b).

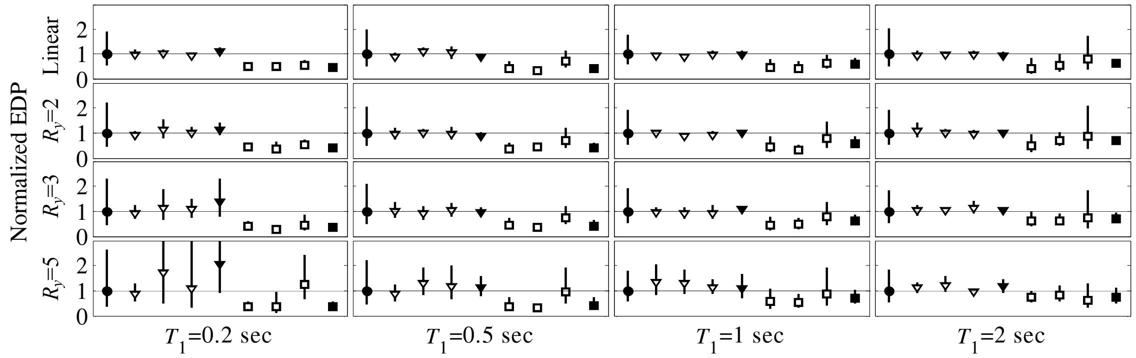
As demonstrated in Figure 4, displacements obtained from sets "ASCE7-Rand" are, in general, inaccurate, and show a large "record-to-record" and "set-to-set" variability. As shown in Figure 4c (e.g., R_y=2 and T_1=1 sec), the underestimation of benchmark displacement values from sets "ASCE7-Rand" is as high as 80%. For R- and T-plan structures, the tendency of sets "ASCE7-Rand" is to overestimate the benchmark displacement values. In Figure 4a (e.g., R_y=3 and T_1=0.2 sec) and Figure 4b (e.g., R_y=2 and T_1=1 sec), the overestimation is greater than 50%. The set "ASCE7-Best" (Fig. 4) gives better accuracy and less record-to-record variability of displacement values for R- and T-plan structures. For L-plan structures, there is no considerable improvement in accuracy when sets "ASCE-Best" are used for estimating displacements as compared to the results from sets "ASCE7-Rand". However, a significant improvement of the record-to-record variability is observed with the use of sets "ASCE7-Best".



(a) Displacement at the center of mass in *y*-direction for R-plan buildings.



(b) Displacement at point c1 in *x*-direction for plan T-plan buildings.



(c) Displacement at point c2 in *x*-direction for L-plan buildings.

● Benchmark ▽ SM-Rand ▼ SM-Best □ ASCE7-Rand ■ ASCE7-Best

Figure 4. Normalized results for the displacement (EDP) at the center of mass and points c1 and c2. For each set the marker and the vertical line represent the median value of the EDP ± σ assuming a lognormal distribution.

These results show again that if the records are selected randomly, the efficiency of the ASCE7 scaling procedure decreases with increasing R_y; the efficiency is achieved only if records are selected on the basis of their spectral shape at T_1; this demonstrates that selection proposed by Reyes and Kalkan (2011, 2012) is adequate to improve the efficiency of the ASCE7 scaling procedure. For short periods and large R_y values, the median of randomly selected sets is not similar to the benchmark values. The random selection of records for the ASCE7 may lead to inconsistent results (Reyes and Kalkan, 2012).

In Figure 4, the displacement values obtained from sets “SM-Rand” are accurate and show a low “record-to-record” and “set-to-set” variability. Only displacements are unsuccessfully estimated for short-period structures designed for high values of R_y (e.g., Fig 4c, R_y=5 and T_1=0.2 sec); for these cases, the overestimation of benchmark values is as high as 80% confirming that the accuracy of SM procedure is expected to diminish for large ductility demands due to high inelastic response (Reyes et al. 2014b). However, designing short-period structures for high R_y values may be unrealistic. The results from "SM-Best" sets provide median displacement values that are much closer to the median values than is achieve by the sets "SM-Rand", "ASCE-Best" and "ASCE-Rand". Note that even for torsionally-flexible structures with strong coupling between lateral and torsional motions, bias in estimated displacements from "SM-Best" is less than 10%. In general, displacements obtained from sets "SM-Best" represent a considerable improvement in accuracy when compared to results from sets "SM-Rand". Additional (yet consistent) results are available in Reyes et al. (2014b) and Quintero (2012).

Multi-Story Buildings

Story drifts at corner c1 (shown by "o" marker in Fig. 2) are presented in Figure 5 thru Figure 7 for the nine structures considered. First, second and third columns of these figures show story drift values in *x*-direction for the benchmark, ASCE7 and SM methods, respectively; the next three columns show similar results in *y*-direction. The markers and horizontal lines represent the median EDP values ± σ assuming a lognormal distribution. To facilitate comparisons, the median benchmark values are kept in all sub-plots as a dashed line. Additionally, results for bending moments in girders in R15, L15 and T15 buildings are shown in Figure 8; selected girders are highlighted in Figure 3 by a diamond and a triangle marker. The bending moments are normalized by peak moment values occurred at any floor.

The records scaled according to the SM method provide median EDPs that are much closer to the benchmark values than is achieved by the ASCE7 scaling procedure and at the same time the record-to-record variability in EDPs is significantly reduced when the SM procedure is implemented. As demonstrated in Figure 5, for the R-plan buildings, the maximum discrepancy in story drifts encountered by scaling records according to the ASCE7 procedure is 30%, whereas when these records are modified by the SM method the maximum discrepancy becomes as low as 10%. Note that the errors obtained with the ASCE7 procedure correspond to underestimations of the median EDPs, while those encountered with SM are mostly overestimations. The overestimations of EDPs are in general lower than 12%.

The record-to-record variability of EDPs is much lesser when a set of records modified by the SM procedure (e.g., columns 3 and 6 of Fig. 5) as compared to the records scaled by the ASCE7 procedure (columns 2 and 5 of Fig. 5). For L-Plan structures ($1.2 \leq \beta \leq 1.4$), the records scaled according to the SM method lead to more accurate estimates of median EDPs than those achieved by the ASCE7 procedure. This improvement in accuracy is demonstrated in Figure 6, where story drifts are shown at corner c1 (Fig. 3). The story drifts from a set of records scaled by the ASCE7 procedure present errors over 20% in all cases as compared to the benchmark story drift values. The maximum 28% error in story drifts encountered with the ASCE7 procedure is only 8% for the SM method. Likewise, the maximum error in bending moments (Fig. 8) is 20% and 4%, respectively for the ASCE7 procedure and SM method. Similar to the results for R- and L-plan structures, EDPs obtained from sets ASCE7 are less accurate than those obtained from SM for T-plan structures..Even for T-plan structures with extreme torsional irregularities ($\beta > 1.4$), the SM method is highly efficient. For instance, columns 5 and 6 of Figure 7 for building T10 show that the maximum discrepancy of 37% in story drifts encountered by scaling records according to the ASCE7 procedure is only 2% when these records are scaled by the SM method. The errors of the SM method are overestimations and on average they are less than 10%. Evidently, the EDPs obtained from the SM method provide improved results in terms of accuracy and efficiency as compared to those obtained with the ASCE7 scaling procedure. For the ASCE7 procedure, the error in bending moments as opposed to the benchmark values (see Fig. 8) is generally smaller than the error in story drifts because bending moments vary slowly with hinge rotation for members that deform beyond the elastic limit at both ends (Reyes, 2009). As a result, even a large error in story drifts leads to small error in the bending moments. Due to limited space, we only show representative set of results here; additional results can be found in Reyes et al. (2014b).

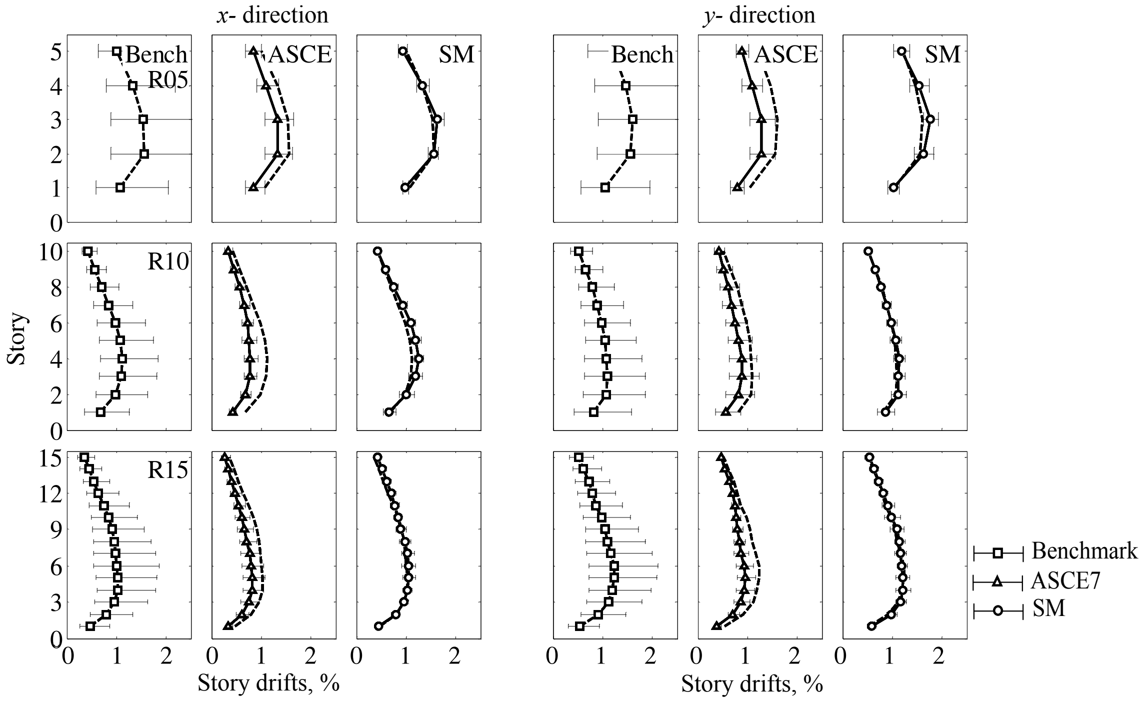


Figure 5. Story drifts in percent in *x*- and *y*-direction in corner c1 (see Fig. 3) for R-Plan structures. In each case the marker and the horizontal line represent the median value of the EDP ± σ assuming a lognormal distribution.

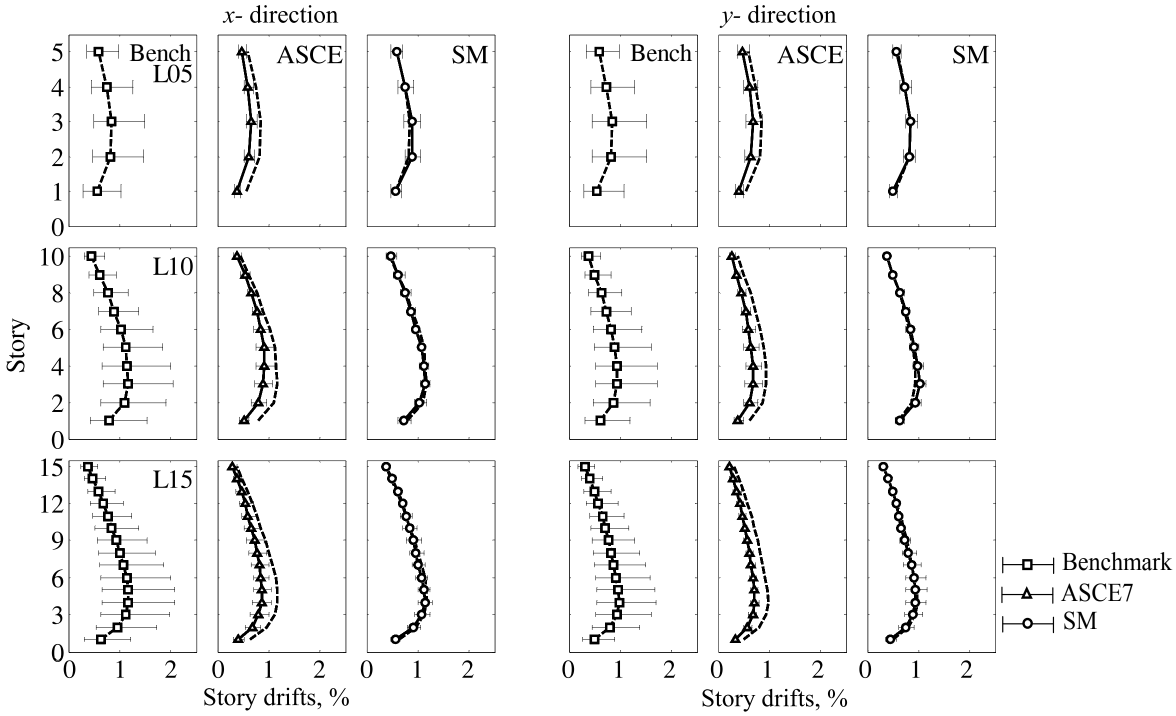


Figure 6. Story drifts in percent in x- and y-direction in corner c1 (see Fig. 3) for L-Plan structures. In each case the marker and the horizontal line represent the median value of the EDP ± σ assuming a lognormal distribution.

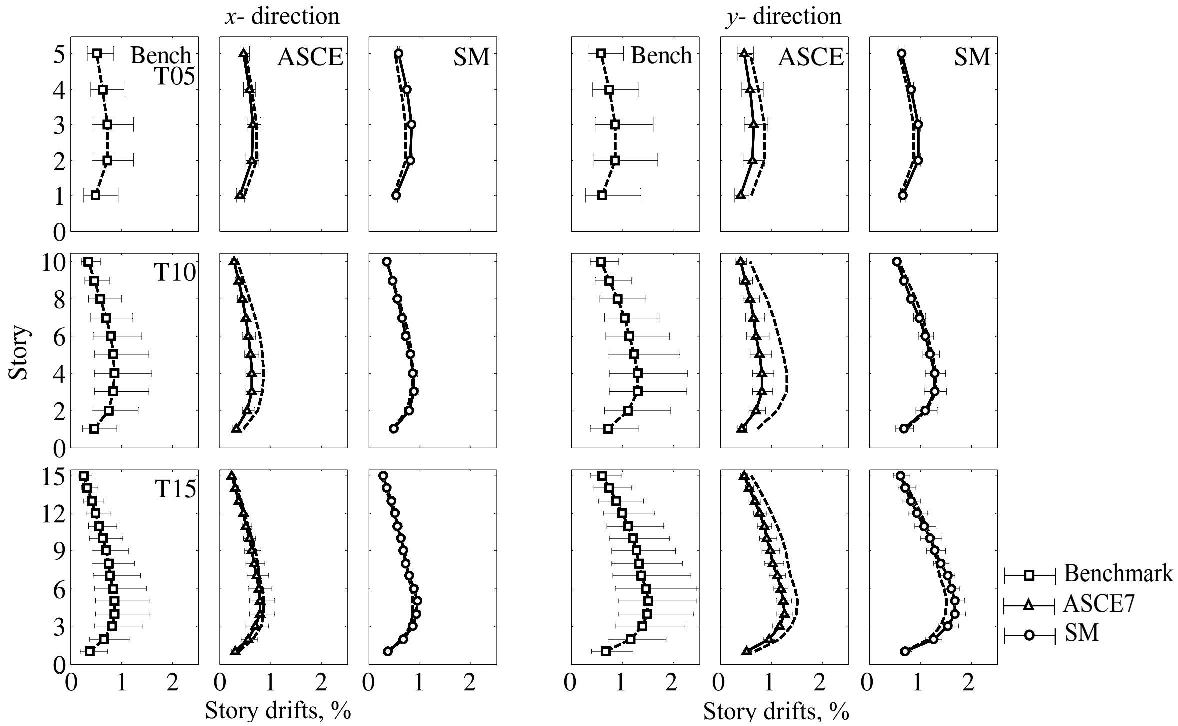


Figure 7. Story drifts in percent in *x*- and *y*-direction in corner c1 (see Fig. 3) for T-Plan structures. In each case the marker and the horizontal line represent the median value of the EDP ± σ assuming a lognormal distribution.

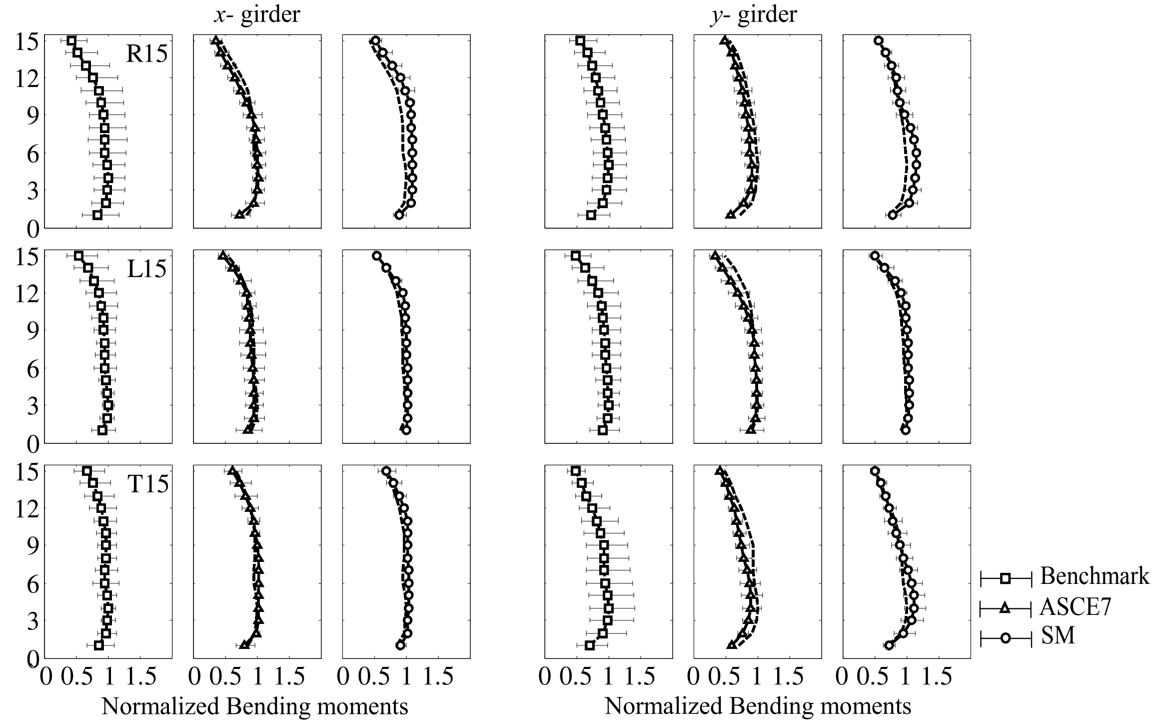


Figure 8. Normalized bending moments in selected girders (see Fig. 3) for R15, L15 and T15 buildings. For each set the marker and the horizontal line represent the median value of the EDP ± σ assuming a lognormal distribution.

CONCLUSIONS

In this study, the accuracy of the SM method was evaluated by comparing the median values of the engineering demand parameters (EDPs) from sets of seven spectrum-matched records against the benchmark values, defined as the median values of the EDPs due to 30 "unscaled" records. The efficiency of the SM method was evaluated by computing the dispersion of the responses; small dispersion indicates that the SM method is efficient. For this evaluation, 3D computer models of 48 single-story and nine multi-story symmetric and asymmetric-plan buildings were utilized. Their structural responses were obtained from subsets of seven records modified by SM and separately by amplitude-scaling according to the ASCE7 ground motion scaling procedure for cross-comparisons. The key conclusions of this study are:

1. For both symmetric- and asymmetric-plan buildings, using spectrum-matched records for nonlinear response-history analysis under bi-directional excitations provides accurate (no or low bias) estimates of median EDP values when compared with a rigorous benchmark.
2. The variability in response associated with inherent aleatoric uncertainty in records is artificially reduced when they are modified according to spectrum-matching procedure. Therefore, spectrum-matched records should not be used to estimate percentile values of response other than the median because it cannot provide the distribution of response. Retaining a certain level of aleatoric variability in EDPs can be an important parameter to be considered for certain projects.
3. Ground motions scaled according to the ASCE7 procedure lead to underestimation of displacements (single-story buildings) and story drifts (multi-story buildings). Even for structures that respond dominantly in the first-"mode", the ASCE7 scaling procedure does not offer accurate demand estimates.
4. Ground motion selection and scaling are two different processes. The ASCE7 scaling procedure does not contemplate a selection phase based on the accuracy and efficiency of the structural responses. According to this standard, a set of seismic records can be randomly selected from an ensemble of ground motions compatible with the site hazard conditions. For single-story buildings, efficiency is achieved only if records are selected based on its spectral shape and the pseudo-acceleration at T_1. The random selection of records for the ASCE7 may lead to inconsistent results.
5. The SM method is found to be more accurate and efficient than the ASCE7 scaling procedure. These improvements are evident in the fact that SM procedure provides median values of EDPs that are much closer to the benchmark values than is achieved by the ASCE7 procedure; furthermore, the dispersion in the EDPs due to seven records around the median is much smaller when records are modified with the SM procedure compared to the ASCE7.

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